

# Progress in the Development of Weather Information Systems for the Cockpit

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## ABSTRACT

Weather is a causal factor in thirty percent of all aviation accidents. Many of these accidents are due to a lack of weather situation awareness by pilots in flight. Provision of strategic weather information during the en route phase of flight can enhance weather situation awareness and enable avoidance of adverse conditions. The National Aeronautics and Space Administration (NASA) has teamed with the Federal Aviation Administration (FAA), National Oceanic and Atmospheric Administration (NOAA), industry and academia to develop technologies for affordable, color graphic display of weather information in the cockpit. These technologies, currently in the initial stages of commercialization by industry, will provide more precise and timely knowledge of the weather and enable pilots in flight to make decisions that result in safer and more efficient operations.

## INTRODUCTION

The NASA has a history of conducting research to address aviation safety and operating challenges. Although there has been significant research over the past twenty years related to weather hazards such as icing, turbulence, lightning and wind shear, weather is still identified as a causal factor in 33% of commercial air carrier accidents and 27% of general aviation (GA) accidents. A continuing area of need has been the collection, processing, distribution and presentation of timely and accurate weather information to pilots in flight.

In the present system, pilots rely primarily on voice communications for in-flight weather updates. Pilots can have difficulty obtaining weather information in a timely manner, assimilating that information into a clear mental picture, and developing a good understanding of changing weather trends. A flight crew that does not have a complete awareness of the weather situation risks encountering adverse weather or may have difficulty

making alternate route decisions. In-flight delivery and presentation of graphic weather updates to the crew should facilitate weather situation awareness and collaboration with Airline Operations Centers (AOC), dispatchers, Flight Service Stations (FSS), and air traffic controllers (ATC) for safer and more efficient operations.

In the early 1990's, a data-link, cockpit weather information system was developed and evaluated by a NASA-industry team [1 & 2]. Piloted simulation studies and flight evaluations on a transport aircraft demonstrated the ability of cockpit graphical weather information to enhance efficiency, safety and situation awareness. In the mid 1990's, NASA, the FAA, industry and academia teamed through the Advanced General Aviation Transport Experiments (AGATE) alliance to develop advanced flight systems for small airplanes, including digital data-linking and cockpit display of weather information. Building on this experience and utilizing advances in forecasting, data processing, transmission, and display technologies, NASA is working with the FAA and industry to accelerate the development and implementation of aviation weather information systems.

## BACKGROUND

In February 1997, the U.S. President announced a national goal to reduce the fatal accident rate for aviation by 80% within ten years. A NASA-sponsored Aviation Safety Investment Strategy Team (ASIST) defined research needs and the relative priority of each based on technology readiness and potential impact on safety. The ASIST participants identified weather accident prevention as a key area to be addressed and prioritized research and development investment areas (Fig. 1). At the top of the list were data dissemination and crew/dispatch/air traffic control monitoring, presentation, and decision aids. Weather product generation and advanced aviation meteorology were also among the top priorities.

In April 1997, the U.S. National Aviation Weather Program Council issued a strategic plan [3] toward providing the improved information and tools needed to enable aviation personnel to make sound and safe decisions regarding weather hazards. This plan was followed by the definition of National Aviation Weather Initiatives [4]. Areas of research and development identified for NASA included multi-functional color cockpit displays of weather hazards; cockpit oriented weather products; flight information services and communications systems; quantification of hazards; and satellite-based, ground-based, and aircraft-based forward-looking technologies for hazard sensing.

Priority	Investment Area
1	Data Dissemination
2	Crew/Dispatch/ATC Monitoring, Presentation, and Decision Aids
3	Icing Hazard Solutions
4	Training
5	Weather Product Generation
6	Advanced Aviation Meteorology
7	Turbulence Hazard Solutions
8	Advanced Technology Vision and Tactical Sensors/Systems
9	Near Term Tactical Sensors/System
10	Strategic Wake Vortex Information
11	Hazard Characterization
12	Runway Contamination

Figure 1. ASIST weather research priorities

NASA established an Aviation Safety Program (AvSP) to develop technologies needed to help the FAA and the aviation industry meet the national safety goal. Within the AvSP, a Weather Accident Prevention Project is developing technologies to reduce weather-related accidents. NASA is pursuing, jointly with industry, those difficult-to-achieve and high technical risk initiatives which industry cannot pursue alone because of a lack of facilities, technical expertise, and research capital. NASA develops and evaluates prototype systems and relies on industry and the FAA to implement the technologies.

In April 1998, the FAA launched its Safer Skies Focused Safety Agenda to address the national goal of reducing the fatal accident rate. Working with the GA industry, the FAA identified controlled flight into terrain and weather as the top-priority causes of fatal GA accidents. One quarter to one third of these accidents was attributed to inadequate weather decision-making. A Joint Steering Committee with members from the GA Coalition, the FAA, and NASA, was created to oversee the GA portion of the Safer Skies initiative. A government and industry GA Weather Joint Safety Analysis Team (JSAT) identified root causes of weather-related accidents and provided prioritized interventions to mitigate them. Following that, a GA Weather Joint Safety Implementation Team (JSIT) recommended programs to address the interventions identified by the JSAT [5]. One of three principal system improvements was "Provide more accurate and precise graphical depictions of the location of weather hazard areas, through improved weather forecasts, pilot weather reports, and weather observations. Effectively deliver this information to pilots on the ground and in the air, to controllers, FSS specialists, and dispatchers."

## COCKPIT WEATHER INFORMATION SYSTEMS

Huettner [6] has traced the history of transport aircraft safety improvement and has identified the information technology revolution as offering the next opportunity for major reduction in accident rates. He notes that aviation weather is the one major variable that is not within the control of technology or aviation system planners. In his view, the optimal weather information system would tell pilots only what they need to know, allow them to go as close to hazardous weather as possible for maximum efficiency of flight, and yet not subject the aircraft or its passengers to conditions that would be hazardous or undesirable. The end objective would be real-time strategic and tactical weather information that could be used to separate aircraft from hazardous weather in the same way that they are separated from other aircraft today.

An Aircraft Owners and Pilots Association (AOPA) Air Safety Foundation (ASF) study [7] has indicated that 27% of GA accidents involve adverse weather conditions. Furthermore, 30% of these weather-related accidents resulted in fatalities; i.e., one out of every twelve GA accidents was a fatal weather-related accident. Continued visual flight rules (VFR) operation into instrument meteorological conditions (IMC) was the deadliest of all types of weather-related accidents, as 82% resulted in fatalities. Ritchie [8] noted that, "Deteriorating weather conditions are frequently the cause of changes in flight objectives. The pilot needs to know quickly where the weather is better and what to do to get there."

At its simplest, an aviation weather information (AWIN) system (Fig. 2) consists of weather products, a means for

distributing the products to the users, and a means to present the information to the users. For a cockpit weather information system, weather information would be gathered by a ground system and converted into products tailored for display in the cockpit. Information would then be distributed to aircraft in flight by transmitting the information to all of the airplanes within range of a transmitter, either by a two-way request-reply link, a broadcast link, or by a combination of the two. Data transmission could be from a network of ground stations, from satellites, or from a hybrid system combining terrestrial and space-based transmitters. Once received on the airplane, the information would be presented in the cockpit on a color display. Some information could also be presented aurally as alerts or synthesized voice. Information from databases resident in the onboard system would be combined with the data-linked weather information to present the weather in the context of surface and airspace features.

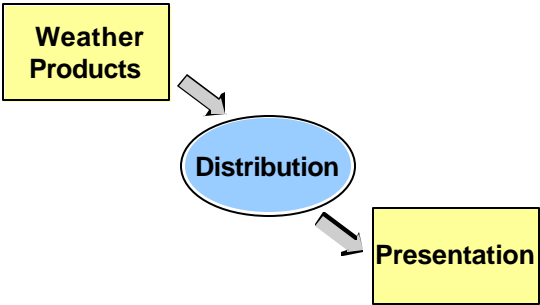


Figure 2. Weather information system elements

The three major system elements can be further subdivided as shown in Figure 3. Presentation of weather information to the flight crew includes the interface with the system, the format of the display and aids to decision making. More than just weather information is needed by operators during the decision process. This includes aircraft capabilities, such as the ability to fly over weather or through icing conditions; operator capabilities, such as the ability to fly in instrument meteorological conditions; and information on flight-path-relevant terrain, obstacles, air space, and traffic. Proximity to terrain, traffic and special use airspace must be factored into the development of plans for weather avoidance. Data links are needed to exchange information between airplanes and ground stations over as much of the flight path as is feasible. Aircraft to aircraft links may be needed for timely exchange of in situ weather reports. Information from onboard sensors may be passed to ground-based weather systems for incorporation in updated forecasts and reports that can be subsequently transmitted to aircraft in flight. Data-link weather information systems are intended to provide information for long-term strategic planning and to augment onboard sensors such as weather radar and lightning detectors that are used as short-term decision

aids. Ultimately, the timeliness, accuracy and presentation of cockpit weather information need to support decisions that result in safe and efficient actions.

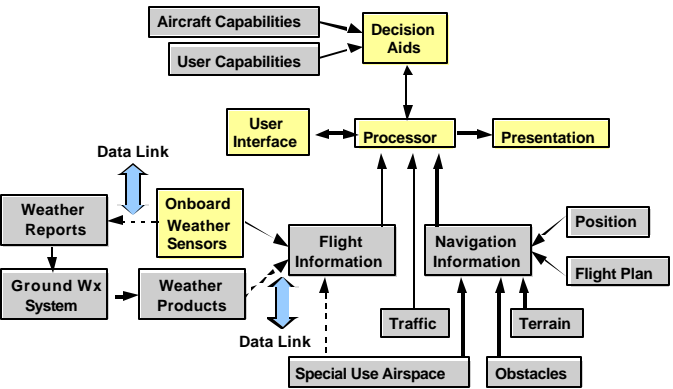


Figure 3. AWIN system components

Weather information systems need connectivity among the flight crew, ATC, dispatchers, and weather providers (Fig. 4). For GA, the dispatcher may be a fixed base operator (FBO) or corporate flight operations office, and the weather provider may be a FSS or a contracted private weather provider. For regional and air carrier operations, the dispatch and weather provider functions may be combined in an AOC.

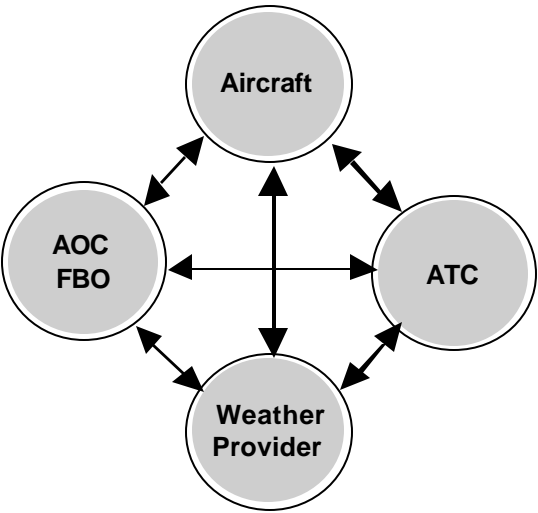


Figure 4. Information exchange

The diverse U.S. pilot user groups provide an added challenge in the implementation of AWIN systems. There are over 600,000 active pilots in the United States and over 200,000 active civil aircraft (comprising approximately 192,000 GA aircraft and 8,000 air carrier aircraft). About 2,000 new aircraft are added each year. To contribute to an improvement in safety in the near future, retrofit issues

and ease of introduction of new weather information technologies onto the flight deck are primary concerns. Requirements for weather information systems reflect the needs of the various aviation communities (Fig. 5). Transport and business aircraft usually have very capable avionics suites, have the ability to fly over or through many types of adverse weather and are flown by two professional pilots. Low-end GA airplanes and rotorcraft are typically flown by a single non-professional pilot and operate at lower altitudes in the weather. Commuter and regional aircraft share some characteristics of transports and some of GA airplanes - they have two professional pilots, but often operate at lower altitudes in the weather. Installed and portable weather display technologies are being evaluated to meet the needs of the different user groups. NASA efforts are focusing on national data-link weather information capabilities for GA, and on national and worldwide capabilities for transport aircraft.

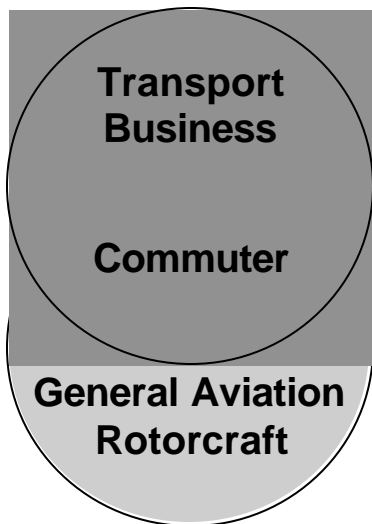


Figure 5. Market segments

A market penetration study [9] has projected that cockpit weather systems will achieve maximum market penetration levels within the next 25 years and will achieve 50% of these levels within the next 8 to 11 years (Fig. 6). Results indicated cockpit weather systems are a viable product concept with strong business cases in the transport, commuter, and business markets. In the GA and rotorcraft market segments, the business cases were sensitive to variations in cost and savings estimates; however, improved safety alone was found to be sufficient motivation for the GA and rotorcraft segments to adopt the technology. The features deemed as necessary for the market success of cockpit weather information systems were identified for each market segment. The main needs for cockpit weather information systems can be addressed through developments for transport and GA airplanes. Business aircraft needs were shown to be very

similar to those of transport aircraft. Commuter aircraft needs combined those of both transport and GA aircraft.

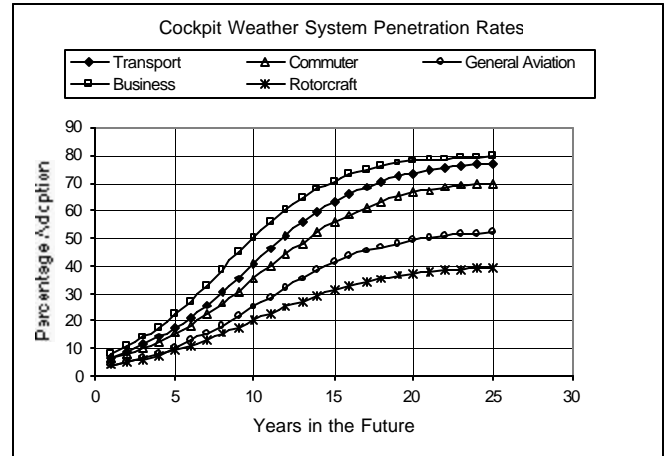


Figure 6. Market penetration estimates for cockpit weather information systems (from reference 9)

Building on the prior work of Crabill and Dash [10], Georgia Tech Research Institute (GTRI) has performed a study for NASA to establish weather information needs by category of user and phase of flight in support of both strategic and tactical decisions [11]. This study included weather phenomena and their impact on aviation, an analysis of weather information needs for each of twelve flight phases, and an assessment of existing weather products to support each flight phase. National Transportation Safety Board reports for weather-related accidents were examined to identify deficiencies in existing weather products. Requirements, including content, geographic and spatial coverage, and timely availability, were compared to weather information available from current sources. The study also defined aviation weather sensor capabilities and needs for hazard avoidance.

In a second study, GTRI investigated the feasibility of developing radiometric sensors for airborne detection of aviation hazards [12]. Three candidate techniques - millimeter-wave sensing of icing conditions; infrared sensing of turbulence; and infrared sensing of ash and acid clouds caused by volcanic eruptions - were identified as good candidates for further research with the possibility of near-term prototyping and flight testing. To support development of such airborne sensors, GTRI identified the need for more extensive modeling and simulation capability and the collection of needed atmospheric data sets.

## WEATHER PRODUCTS

The FAA, through its Aviation Weather Research Program, is working to reduce weather-related accidents

and incidents and to reduce the impact of weather on the capacity and efficiency of the National Airspace System (NAS). Research teams have been established to develop improvements in specific areas of weather sensing, modeling and forecasting. An Aviation Digital Data Service (ADDs) has been implemented on the internet to provide end users access to both operational and experimental weather products. Prior to flight, pilots will be able to acquire route-specific graphics of key variables such as icing, turbulence, clouds, and thunderstorms.

Through a cooperative effort with NASA, Rockwell has developed a flight-planning tool to improve preflight weather briefings for GA pilots. The tool integrates text-based and graphical weather information sources and filters information to display to the pilot only what is relevant to the intended route and time of flight. A decision support model has been included that advises the pilot of the probability of completing the flight as planned based on pilot preferences, risk tolerance and aircraft equipment. NASA and Rockwell are also utilizing these weather information processing capabilities as part of an airborne hazard awareness system that combines data-link, in situ and look-ahead information sources on-board an airplane.

NASA has been working with industry to adapt established and new weather products for in-flight presentation and use by GA and commercial air transport pilots. NASA is also investigating in situ and remote sensing capabilities to complement existing weather data sources. Current emphasis is on development of enhancements to on-board weather radar and development of automated weather reporting from small aircraft.

**ENHANCED WEATHER RADAR** - Through a cooperative research agreement with NASA, Rockwell is developing an enhanced on-board weather information system that will monitor both airborne and ground-based radar images and provide automatic storm analysis. The system, called Enhanced Weather Radar (EWxR), integrates information from an on-board XBand weather radar with up-linked ground weather radar information and displays it to the crew properly oriented to aircraft heading (Fig. 7). A "fence" is drawn on the display to indicate the boundary between the on-board and the data-linked radar data. Weather radar storm-tracking algorithms that estimate the speed, direction, and cloud-top height of storm cells have been demonstrated. A prototype system that combines in situ and up-linked weather radar images has been evaluated on a Rockwell Sabreliner and a NASA B-757. A NASA transport cockpit simulator is being used to further study the combining of up-linked time-delayed strategic information with on-board real-time tactical radar information. This will be supplemented by further flight evaluations using the NASA B-757.

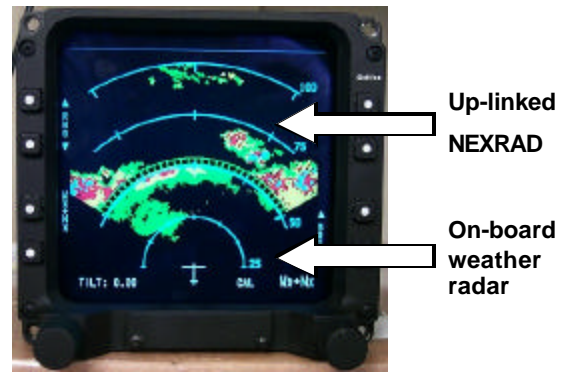


Figure 7. Rockwell Enhanced Weather Radar display

**AIRBORNE WEATHER REPORTING** - Automated airborne weather reporting utilizes instrumented aircraft in flight as weather observing stations that report in situ conditions. Currently, the Meteorological Data Collection and Reporting System (MDCRS) collects position, temperature and wind data transmitted to the ground from participating jet transport aircraft via the Aircraft Communications Addressing and Reporting System (ACARS) and sends the information to the National Weather Service (NWS) for input to forecast models. As the airplanes climb out of and descend into terminal areas, they provide atmospheric soundings from the surface to cruise altitudes. Because these airplanes operate into and out of only about sixty major airports, the atmospheric soundings are limited to these locations. During cruise, most of the observations are at high altitude along defined airline routes. About 80,000 observations are provided each day from six participating operators. Moisture in the atmosphere, a key ingredient in weather phenomena, occurs predominantly at altitudes below 25,000 feet. Thus, aircraft operating at the lower altitudes have the potential to make a significant contribution to improving weather products through the collection and dissemination of in-flight weather observations (Fig. 8).

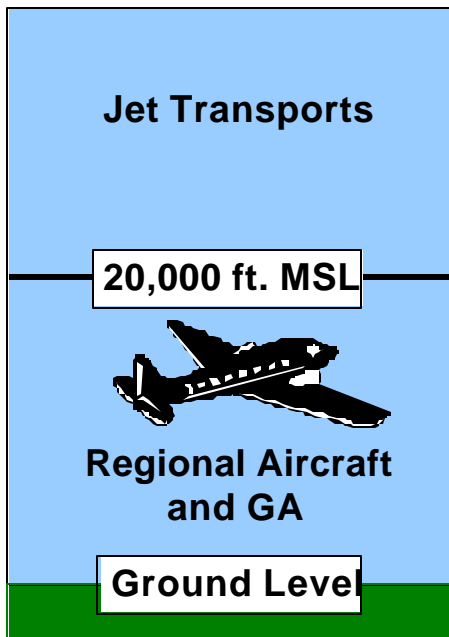


Figure 8. Airborne weather reporting coverage

density, cruise altitudes, professional maintenance and low nonrecurring cost. The analysis targeted provision of 160,000 observations a day from TAMDAR. The resulting business case for TAMDAR was found to be very positive [14].

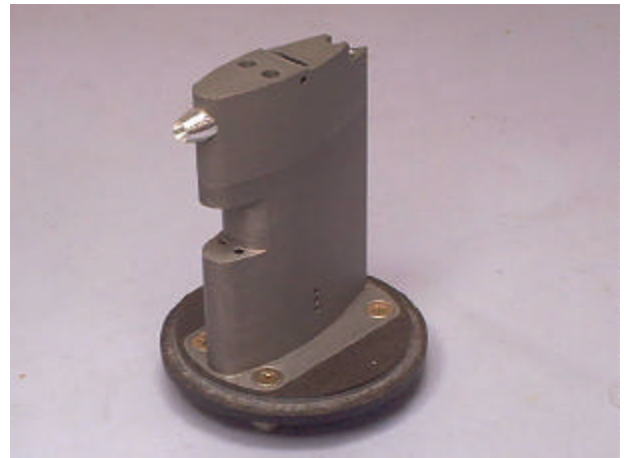


Figure 9. Prototype TAMDAR sensor

More frequent weather observations can improve the forecasts from both current and future atmospheric models. These weather observations are desired on a regular basis if users are to depend upon the availability of the resulting enhanced reporting and forecasting capabilities. Aircraft, such as those operated by regional airlines and package carriers, operated over defined routes on a regular basis and capable of operating in IMC, appear to be the best candidates for airborne weather reporting. Implementation would require viable weather sensors and an extensive data-link communication system.

NASA is working with the FAA, NWS and industry to develop such capabilities for small aircraft. The NASA, FAA and NWS have jointly addressed a concept of operations, sensor requirements, and reporting frequency. A compact airborne sensor package, referred to as a Tropospheric Airborne Meteorological Data Reporting (TAMDAR) sensor (Fig. 9) is being developed to measure temperature, humidity, wind, turbulence, and ice accretion [13]. A prototype sensor is currently being evaluated in flight against established atmospheric measurement systems on airplanes operated by the University of North Dakota and by NASA (Fig. 10). Communications architectures and technologies are also being developed for distribution of data to the National Weather Service, Flight Service Stations and other aircraft in flight.

Old Dominion University (ODU) has conducted a feasibility study of TAMDAR for NASA and the FAA. TAMDAR was seen as an important complement to the MDCRS for the improvement of short-term aviation weather forecasts. Regional airlines and package carriers were identified as best for meeting the desired predictability of routes, flight



Figure 10. TAMDAR sensor mounted under wing of NASA DHC-6

## DISTRIBUTION

As previously noted, the ASIST participants identified data dissemination as the top research and development priority for aviation weather accident prevention. Furthermore, the National Aviation Weather Initiatives [4] and the GA JSIT [5] activities also strongly recommended the need for improved dissemination of weather information to ground and airborne users.

Distribution of the information can be generally classified along four communications domains: ground-to-ground, ground-to-air, air-to-ground and air-to-air. It is generally

accepted that there is a wealth of graphical weather information available from a variety of public and private sources easily accessible on the ground via numerous mechanisms such as the internet. The supporting ground-to-ground communications infrastructure is relatively mature with the exception of needed standardization of weather data formats for more efficient ground-to-ground transfer. The greatest technical challenge is with respect to the latter three *wireless* communications domains (ground-to-air, air-to-ground and air-to-air). NASA, in partnership with the FAA, the industry and academia is addressing this technical challenge by: defining the weather information communications requirements; developing guidelines for optimal supporting communications architectures; and developing and validating needed network and communications technologies to support weather information distribution to and from aircraft.

**REQUIREMENTS** - Although the information revolution of the last 25 years has dramatically transformed the consumer and business sectors of the US. economy, aviation has yet to truly benefit from these technological advances; analog voice remains the primary means of communications for aviation. The national and worldwide dissemination of graphical weather products to the cockpit poses a unique and significant communications requirement- a *digital* datalink is required with the necessary *capacity*, *coverage* and *timeliness* to handle what is probably the most bandwidth-intensive application in aviation (graphical weather).

Through a combination of in-house and contracted analyses [15, 16 and 17], NASA has investigated the communications requirements and associated datalink architectures optimal for the delivery of graphical weather products to the GA and commercial air transport cockpit. These studies established current, mid-term (2007) and long-term (2015) weather communications needs and resulting requirements via expert interviews, published literature (such as the FAA's *NAS Architecture 4.0* and relevant RTCA documents [18]), and internal projections. Key results from the studies include:

**Shared infrastructure** - Weather information alone cannot justify its own datalink infrastructure; rather, it must share along with other flight information such as special use airspace and NAS status. Cockpit weather information is intended for strategic rather than tactical decision-making and is considered advisory-only and not critical in nature. This allows commercial networks to be candidates for supplying this information- as opposed to government-owned and operated systems- offering the potential for lower cost via increased market competition and open standards for interoperability with other on-board avionics such as multifunction displays (MFDs).

**Bandwidth** - Estimates of expected data loads for weather information are contained in RTCA DO-237 [18] for lossless compression. Weather products are specified for

both en route and terminal areas. A NASA-sponsored study by Lockheed Martin [15] also investigated weather data loading with weather products considered in terms of three "decision regions" - tactical (125 nm radius), near-term strategic (500 nm radius) and far-term strategic (1500 nm radius). A follow-on NASA-sponsored study [16] made yet a third estimate of the data loads for weather-related Flight Information Services (FIS). Overall, there still remains some uncertainty about the actual set of weather products that will comprise FIS in the future and thus the resulting transmission capacity that will be required. Furthermore, the type of communications architecture (broadcast or two-way) and type of data compression used also affect the system capacity estimates. Despite the uncertainty, all of the analyses indicated minimal satisfaction of requirements with channel rates of 10's of Kbps in the near-term (2007) and required channel rates of 100's of Kbps in the long-term (2007-2015).

**Datalink Architecture** - Given the requirements, NASA commissioned a comprehensive study [16] to derive the optimal datalink architecture in 2007 and 2015 for the air/ground dissemination of weather-related FIS. The study investigated broadcast and two-way addressable methods via terrestrial (VHF, UHF and L-Band) and satellite (narrowband and broadband) datalinks. It concluded that broadcast/one-way was more bandwidth efficient than two-way/addressed methods. In addition, it noted that VHF digital broadcast networks could minimally satisfy the 2007 requirement for disseminating regional weather products, but they would have difficulty providing national products due to the limited number of frequencies available at VHF and the need for frequency sharing. It recommended that broadband datalinks, preferably with a national coverage footprint operating at a less constrained frequency spectrum such as satellites, would be more suitable to provide national FIS products. Internal follow-on analyses by NASA have indicated that a hybrid combination of terrestrial datalinks for airport/terminal area regional products and satellite datalinks for continental U.S. and worldwide products is an optimal solution for provision of FIS.

In further defining such architectures, a number of systems have been studied [17] including VHF datalinks and existing and proposed satellite, cellular and radio systems that could be utilized in the 2005 timeframe. Terrestrial VHF Datalink (VDL) Mode 2 networks being fielded by ARINC and SITA can provide coverage over the continental U.S. Aircell can provide coverage over the continental U.S., but communications costs were identified as an issue. Third-generation digital wireless systems have performance limitations with increased airspeeds that require further investigation and resolution. Among satellite systems, low-earth-orbit (LEO) and medium-earth-orbit (MEO) systems could provide coverage with reduced latencies compared to geosynchronous satellites; however, they are considered high risk and are very expensive to maintain. The

geosynchronous Inmarsat system currently provides highly reliable voice and data service throughout much of the world; however, high service and equipment costs have limited market penetration. Satellite digital audio radio services such as XM radio and Sirius may also provide useful one-way broadcast from satellites to aircraft.

A preliminary communications architecture analysis has been performed for the TAMDAR system [19, 20]. A key challenge to realizing TAMDAR is the datalink, ground reception, and distribution of the airborne sensor data. NASA and Johns Hopkins University Applied Physics Laboratory have completed a preliminary technical analysis, modeling and simulation of potential TAMDAR datalink architectures. Three datalink approaches were investigated: ground-based, satellite-based (SATCOM) and a hybrid mix of ground/satellite. The study focused on GA and regional aircraft users in the 2003 timeframe. Datalink requirements were identified and developed architectures were ranked based on ability to meet requirements. For SATCOM, three systems appeared viable. For ground-based, the Automatic Dependent Surveillance-Broadcast (ADS-B) systems could satisfy TAMDAR needs; however, their lack of national infrastructure precludes them in the near-term. Commercial cellular systems, with extensive infrastructure, had difficulty addressing air-to-air requirements (as did SATCOM). The strongest options identified were the two-way addressable datalinks (such as VDL Mode 2) intended for aviation applications.

**NETWORK TECHNOLOGIES** - Through studies with the Massachusetts Institute of Technology Lincoln Laboratory, CNS Inc., and ARINC, NASA has investigated the communications network protocols optimal for FIS. Both the Internet Protocol (IP) and the International Civil Aviation Organization (ICAO) Aeronautical Telecommunications Network (ATN) standards have been investigated. With the ATN, messages are delivered regardless of the communication link used as long it is ATN-compliant. The specific link need only provide the required communication performance for the application. The implementation timeframe of ATN, however, may be inadequate to provide a significant level of weather data dissemination by 2007. ATN is by design a two-way addressed protocol with all users assigned a unique ICAO identifier address. This is counter to the broadcast nature of FIS information and studies to date have shown that use of the ATN for FIS is extremely network inefficient due to the need to address each recipient individually. The ATN has been designed primarily for airline operators and may prove too expensive for some user classes, such as low-end GA that would have to equip with ATN-compliant hardware. The ATN is currently being implemented worldwide by the major airline communications service providers (ARINC and SITA) as part of their upgrade from the capacity-limited ACARS to the ATN/VDL Mode 2 system to support advanced future airline operations and air traffic management applications for the next 20-30 years. These applications are primarily two-way in nature.

NASA is conducting joint research with these providers in the formatting of the weather information and adapting the ATN protocol so that FIS can be carried over ATN more efficiently. NASA is also performing research into next-generation IP protocols (such as version 6) incorporating priority, mobility, and quality of service performance for FIS. Use of the popular IP standard is appealing due to the large investment in technology and standards by the commercial and consumer electronics sectors. Aviation has at most several hundred thousand potential users for any given technology; whereas, consumer technologies are driven by millions and perhaps more than a billion users. This vast user base has the potential to greatly enhance utility while reducing the cost for aviation.

**GROUND-BASED DATALINKS** - Ground-based digital datalink technologies have been developed and used to demonstrate in-flight dissemination of graphical weather information to the GA and air transport cockpit. Through a NASA cooperative research agreement with Honeywell, a VDL-Mode 2 datalink operating in the aeronautical VHF frequency band has been demonstrated that is capable of broadcast data rates up to 31.5 kilobits/second (Fig. 11). Also, via a NASA cooperative research agreement with ARNAV Systems, a VHF band datalink using Gaussian Mean Shift Keying (GMSK) has been demonstrated that is capable of data rates up to 10 kilobits/second (Fig. 12). Via another cooperative agreement with Honeywell, an air transport category datalink implementation utilizing the sky phone system (commonly used for seat back passenger telephony) and dial-up digital modem technology has been developed. This system has been utilized on the NASA B-757 transport systems research aircraft and has been used by United Airlines for in-service evaluations of cockpit weather information delivery. These near-term datalink technology developments offer viable rapid implementation of graphical weather information systems for GA and air transport operations. Successful technology transfer has been demonstrated via the selection of the Honeywell and ARNAV datalink systems for the FAA's Flight Information Services Data Link (FISDL) program -building national VHF datalink infrastructures for the purpose of graphical weather provision to general aviation.



Figure 11. Honeywell VHF Datalink Mode 2 ground station



Figure 12. ARNAV datalink avionics installed in a Cessna 180

**SATELLITE DATALINKS** - Through partnerships with industry, NASA is also developing and validating satellite communications (SATCOM) datalinks for delivery of weather information to GA and air transport aircraft.

Via a contract with NASA, ViGYAN has developed a satellite-based aviation weather information system known as the Pilot Weather Advisor to broadcast text and graphical weather information to aviation users at any altitude and location. In addition, NASA has been investigating the use of state-of-the-art satellite digital audio radio systems (SDARS) for delivery of weather information. SDARS are currently the most powerful commercial satellites ever orbited and have recently begun offering national compact disc-quality digital audio radio services (via XM Radio and Sirius) to home and automotive subscribers. Internationally, WorldSpace has been offering similar services to Africa, Asia and soon to South America.

NASA, via a partnership with WorldSpace and Rockwell Collins, investigated the feasibility of SDARS for FIS transmission to a general aviation aircraft in South Africa during September 1999 using the AfriStar SDARS satellite (Fig. 13). With excellent performance demonstrated in South Africa, NASA, Rockwell and WorldSpace have continued the investigation by partnering with Jeppessen and American Airlines to evaluate the dissemination of graphical weather products to airliners flying oceanic routes between the U.S. and the Pacific Rim [21] (Fig. 14). An SDARS-type of capability could improve timely access to weather information over oceanic routes and would greatly benefit the adjustment of flight paths to improve flight efficiency and avoid hazardous weather (Fig. 15). With domestic SDARS services underway, NASA is establishing similar partnerships to evaluate SDARS technology for U.S. aviation weather services.

Figure 13. Satellite patch antenna installation on Cessna 172



Figure 14. Installation of patch antenna and radome on Boeing 777

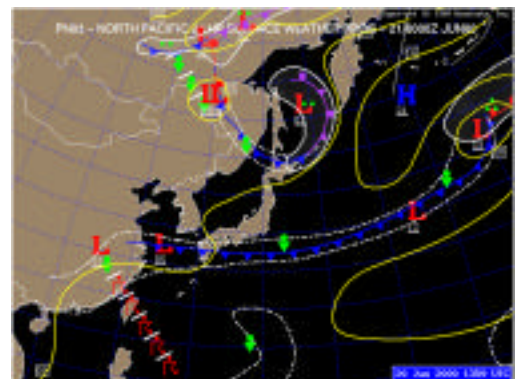


Figure 15. Weather graphics transmitted to B-777s via satellite

NASA has worked with Boeing and the Department of Defense to develop broadband SATCOM datalinks and phased array antennas for aeronautical applications. A prototype Ku-band SATCOM datalink and associated antenna system was flown on a NASA DC-8 aircraft demonstrating two-way broadband communications of 256 Kbps off the aircraft and 2 Mbps to the aircraft (Fig. 16). This system has recently been installed on a NASA B-757 aircraft for further aviation weather experiments. Boeing has recently received a Federal Communications Commission license allowing passengers to transmit and receive broadband data in the air, above the U.S. and territorial waters, using its newly announced Connexion in-flight internet, e-mail and television service [22]. This service is based on the Ku-band datalink technology jointly developed and evaluated by NASA, Boeing and the Department of Defense. The company expects to roll out the first airliners equipped for in-flight broadband transmissions by early 2003. Lufthansa is the launch airline customer.



Figure 16. NASA DC-8 aircraft performing satellite system characterization

## PRESENTATION

For aviation safety to be improved through better weather information, appropriate weather information must be made available; the information must be presented in an easy-to-use manner; and pilots must be aided in gathering the right information, interpreting the information and taking the best action. The first step to providing such assistance is to understand what weather information is needed to make decisions during each phase of flight. Pilot weather information needs have been identified for each of twelve phases of flight [10 & 11]. In conjunction with Embry-Riddle Aeronautical University, NASA has conducted a survey to characterize pilots' acquisition and usage of aviation weather information. Results indicated what sources of pre-flight and in-flight weather information are used most and what value pilots place on the various weather products available [23].

Business aviation has an excellent safety record and can provide insight on the effects of weather information on piloting. Business flights can arise on short notice (minimizing the time to monitor weather trends); can have varied destinations (reducing pilot familiarity with local weather conditions); and can be to small airfields with limited weather advisory information. A task analysis has been conducted with eight "high-time" business jet pilots [24] to study how they access weather information and use it to make decisions. Three high-level pilot goals were identified: flight safety; flight efficiency; and passenger satisfaction. Twenty-two weather-related critical decisions were identified for six phases of flight: preflight planning; taxi and takeoff; climb; cruise; descent and approach; and landing and taxiing. Challenging weather scenarios and novice errors identified in this study provide the basis for experimental scenarios and metrics for evaluations of aviation weather information systems.

To make the best use of emerging technologies, weather information system requirements must be defined in terms of the user's operational needs. Huettner [6] notes "we must know what decisions will be made and by whom. What information will be needed and who will have to communicate with whom to make decisions. Then we must know if decisions can be made unilaterally or whether negotiation is necessary. Successful negotiation depends on knowing the goals, intentions, and constraints (safety, economy, passenger convenience) of the other parties; the level and types of uncertainty induced by weather and actual versus planned action; the mutual trust of the parties involved; and the risk and workload tolerance of the parties."

The General Aviation Manufacturers Association (GAMA) has published recommended practices for addressing human factors in the design, development and evaluation of small airplane (FAR Part 23) flight decks and associated systems [25]. Guidance is provided for both new and retrofit installations. Guidelines are also provided for assessing the impact on workload in terms of difficulty for the pilot to fly the airplane while operating the system and the difficulty for the pilot to use the system while flying the airplane.

Sponsored by NASA and the FAA, the Research Triangle Institute's (RTI) Center for Aerospace Technology is conducting experiments to investigate pilot performance using a prototype cockpit weather display in a full-mission simulator (Fig. 17). Flight scenarios impacted by adverse weather are being used to assess textual and graphic weather information presentation formats and to identify potential concerns that might result from the use of these products by general aviation pilots. The latency (delay) in delivery of weather updates to the cockpit via data link is replicated in these studies. Results are reflected in design guidance and operational guidelines published in RTCA standards, FAA Advisory Circulars, and the Aeronautical Information Manual.



Figure 17. General Aviation Cockpit Research Facility at RTI

Initial experiments [26-28] have investigated early concepts for graphic presentation of weather data and the effects on pilot navigation decisions. Results of these studies have supported the need to display the airplane's position as part of graphic weather depictions; to provide an indication of distance or range; and to present the age of the weather information rather than the time of creation. The resolution of the graphic depictions of data-linked NEXRAD radar information was shown to affect pilot navigation decisions in adverse weather situations. The current experiment in this series is studying the usefulness of trend information presented via "looping" of NEXRAD images and display of the National Convective Weather Forecast (NCWF) product.

A prototype data-link cockpit weather information system (Fig. 18) has been used in a flight test to study how well general aviation pilots detect convective weather in flight with different weather information sources [29-31]. Pilot weather situation awareness was compared when provided with weather cues typical of a flight in visual meteorological conditions (VMC), cues typical of flight in instrument meteorological conditions (IMC), and cues typical of flight in IMC but augmented with a graphical weather information system. Subjects provided with normal weather information via radio (aural information) augmented by graphic display of data-linked information were markedly better at detecting cells than when using aural or aural plus out-the-window weather information sources. The weather information sources were seen to complement each other, such that the best in-flight convective weather situation awareness might be achieved when pilots use all three weather sources (aural, out-the-window and graphic) together.



Figure 18. Prototype cockpit weather display connected to airplane via tether

A flight experiment has been conducted to study the effects of the location in the cockpit of a graphic weather information display on the ability of general aviation pilots to access weather information while flying in visual and instrument meteorological conditions [32]. Three different display locations - panel, yoke and kneeboard - were studied. Pilots preferred the display mounted in the center of the instrument panel. Second choice was a display mounted in the center of the control yoke (Fig. 19). Overall, pilots were able to access weather information much faster via the data-link system than via voice transmissions from ground stations such as Automated Surface Observing Systems (ASOS).



Figure 19. Yoke-mounted weather display

The RTCA has published Minimum Aviation System Performance Standards (MASPS) for Flight Information Services-Broadcast (FIS-B) Data Link [33] for broadcast systems providing non-control advisory information used by pilots to improve safety and efficiency of operations in the National Airspace System (NAS). Functional and performance requirements; procedures for performance verification, and guidelines for information display are included. These standards incorporate knowledge gained

from NASA and industry research and development and can be used by the FAA Flight Standards and Aircraft Certification Services to develop criteria for approval of FIS-B airborne equipment.

Recognizing the interest in self-contained electronic flight information management devices, i.e. electronic flight bags (EFB), the FAA sponsored the Volpe National Transportation Systems Center to prepare reference material [34] for evaluation and operational approval of such devices. Approval will necessitate understanding how the device functions and is used by the crew; how it interacts with other flight deck equipment; how its use impacts operating procedures; and how operators are trained. Initially three EFB functions have been addressed: electronic documents; electronic checklists; and flight performance calculations. Advanced EFB functions such as approach plates, electronic messaging and weather display are to be addressed in a future version of the document.

## **IMPLEMENTATION**

Much progress has been made in the past few years in the development and fielding of AWIN systems for GA. NASA and FAA partnerships with industry have been instrumental in stimulating implementation.

In the early 1990's, a Pilot Weather Advisor system was developed through a NASA Small Business Innovative Research contract with ViGYAN. Text and graphic weather information were transmitted via satellite from a ground station to airplanes in flight. The Pilot Weather Advisor has been demonstrated on several different display devices and will enter the marketplace in 2002 as the WeatherStream Pilot Weather Advisor. This system provides coverage at all altitudes and can service a broad spectrum of aviation users operating over the U.S. and offshore waters.

In response to a 1997 NASA research announcement, ARNAV Systems and NavRadio (now Honeywell International, Inc.) were selected to work with NASA to develop capabilities for national GA weather information systems. These cost-shared research and development efforts began in early 1998. Advanced weather products developed by the National Center for Atmospheric Research (NCAR) have been adapted by ARNAV for use in the cockpit and flight evaluations have been conducted with these products. An affordable, VDL Mode 2-based weather and FIS broadcast, reception, and display system for GA has been developed by Honeywell International. Ongoing cooperative efforts with both ARNAV and Honeywell are expanding initial FISDL capabilities by developing and validating more advanced weather products, data links and display capabilities.

In May of 1998, the FAA published an Airborne FIS Policy Statement based on an industry petition through the

General Aviation Coalition. The FAA's stated goal was to use digital data link to deliver information to the pilot and to do this by using private sector FIS capabilities to bring services and products to the market place quickly and efficiently. FIS products include advisory information such as text and graphical weather, special use airspace information and notices to airmen. The current FAA FISDL policy specifies a broadcast system providing coverage similar to current Flight Watch service, i.e. 5,000 ft AGL to 17,500 ft MSL nationwide (Fig. 20). Coverage from the surface to 45,000 ft MSL is desired where possible. A specified basic set of weather products is to be broadcast for free to any equipped aircraft; a subscription fee may be charged for value added products such as graphic NEXRAD mosaics. In exchange for a pair of 25 kHz VHF frequencies provided by the FAA, a company would fund the development of the broadcast network and could offer FIS subscription service.

On July 30, 1999, the FAA announced that it would partner with two companies, ARNAV Systems, Inc. and Honeywell International, Inc., to enable Flight Information Services via Data Link (FISDL) [35]. Users would need to equip their aircraft with a VHF data radio and a color multi-function display to receive and view the information. Both companies have developed the airborne receivers and display devices and are currently fielding the needed infrastructure of ground stations. However, the limitation of two frequencies for each of the companies has resulted in communications architectures that may suffer from co-channel interference at altitudes above 17,500 ft MSL.

The RTCA has published MASPS [33] for cockpit display of weather information. The FAA has developed and implemented a review and approval process for the weather products that are developed by the two FISDL providers. The FAA has also published guidance for pilots in the Aeronautical Information Manual [36] regarding use of FIS-B.

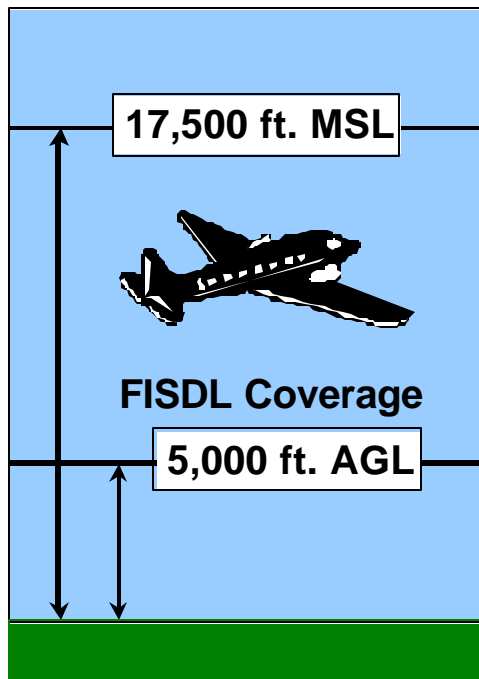


Figure 20. FISDL coverage

As shown in Figure 21, numerous companies have formed alliances to combine weather information, communications and display technologies into systems to deliver weather information to the cockpit of general aviation airplanes. A variety of display devices and information delivery architectures are being employed to address the varied needs of GA operators [37].

Company	System	Data Link Employed
AirCell <a href="http://www.aircell.com">www.aircell.com</a>	Flight Guardian	Terrestrial cellular telephone
ARNAV Systems Inc. <a href="http://www.arnav.com">www.arnav.com</a>	WxLink	Terrestrial and satellite broadcast and request-reply
Avidyne <a href="http://www.avidyne.com">www.avidyne.com</a>	FlightMax	Orbcomm LEO satellite request-reply
ControlVision <a href="http://www.controlvision.com">www.controlvision.com</a>	Anywhere Wx	GlobalStar satellite request-reply
Echo Flight <a href="http://www.echoflight.com">www.echoflight.com</a>	Flight Cheetah Meteorlogix	Orbcomm LEO satellite request-reply
FlyTimer <a href="http://www.flytimer.com">www.flytimer.com</a>	WxMate	ARINC ACARS GLOBALink two-way
Garmin <a href="http://www.garmin.com">www.garmin.com</a>	Echo Flight Meteorlogix	Orbcomm LEO satellite request-reply
Honeywell Bendix/King <a href="http://www.bendixking.com">www.bendixking.com</a>	Wingman	Terrestrial VDL Mode 2 broadcast
SATELLINK Technologies	Merlin	Mobile Satellite Ventures

<a href="http://www.satellinktech.com">www.satellinktech.com</a>		geosynchronous satellite broadcast
WeatherStream <a href="http://www.wxstream.com">www.wxstream.com</a>	Pilot Weather Advisor	Mobile Satellite Ventures geosynchronous satellite broadcast

Figure 21. Implementation of cockpit weather information systems

Honeywell International, in a joint effort with NASA, has developed a Weather Information Network (WINN) capable of providing graphical weather information to the cockpit of commercial and business aircraft flying anywhere in the world. The network includes airborne displays, airborne and ground-based servers, and multiple providers of weather products and data link services. An open architecture has been adopted to accommodate any kind of data link technology. Both a satellite-based link and a terrestrial VHF/UHF telephone link have been evaluated. Several different types of weather information can be overlaid or viewed individually. Since the inception of this work in 1998, evaluations have been performed with systems installed in a Citation business jet, a United Airlines B-777 full flight simulator, NASA's B-757 transport research airplane (Fig. 22), and a United Airlines Airbus A320 (Fig. 23). During the winter of 2001, United Airlines conducted over 40 in-service evaluation flights with the WINN system incorporated in a prototype electronic flight bag. Aircraft position information was provided by a portable global positioning system (GPS). Weather products were delivered to the airplane via a GTE Airphone and included airport observations (METARS), terminal area forecasts (TAF), ground weather radar reflectivity (NEXRAD), turbulence, significant weather cautions (graphic SIGMETs), and satellite cloud images. Information was displayed on a Fujitsu Pen Table. An average of 1 to 2 percent time savings (and thus cost) per leg was attributed to increased weather situation awareness. Based on these trials, a potential reduction in Aircraft Communications Addressing and Reporting System (ACARS) messaging traffic (and thus cost) of 40 to 50 percent was estimated.



Figure 22. WINN display in NASA B-757



Figure 23. WINN display in Airbus A320

## ADDITIONAL RESEARCH AND DEVELOPMENT

As first generation data-link cockpit weather information systems are being fielded, NASA is working on enhancements to these systems as well as developing new technologies for the next generation of AWIN systems. In 2005, the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) satellite will be launched by a joint NASA, NWS, Navy and Air Force team as the precursor to a new generation of high-resolution weather satellites. NASA is working with the FAA's aviation weather product development teams to increase the use of satellite weather data to improve both current and future aviation weather forecasting and reporting. Data generated during developmental tests of the GIFTS instruments will be used to create and evaluate prototype aviation weather products so that these products will be ready for implementation when the satellite becomes operational.

Viable datalink communication continues to be a critical need in enabling aviation weather information systems. NASA is continuing to explore communications architectures and technologies that will provide increased data transmission performance at reduced cost. Technologies being developed by the automotive and trucking industry for Intelligent Transportation Systems are being studied [38] to determine the possibility of using similar systems in the cockpits of general aviation aircraft. These in-vehicle information systems combine communications, information processing, and control functions.

NASA is continuing to examine how data-linked weather information can best be used with other existing weather information available to pilots in flight. On-board radar, lightning detection systems, in situ reports from other

aircraft and information from collaboration with ground weather briefers need to be combined effectively with the products delivered to the pilot via data link. As noted by Horne [37], "Like other technological advances, however, any safety benefits depend solely on pilot judgement. You can have all the weather data in the world and still make bone-headed decisions." With a data link weather information infrastructure in place, means need to be developed to help the pilot search the information sources available, identify trends and changes affecting his or her flight, and ultimately to make timely decisions to avoid hazardous weather.

## SUMMARY

Weather-related accidents comprise 33% of the commercial air carrier accidents and 27% of GA accidents. Using the inputs of industry and government, the research needed for the reduction of weather-related accidents has been identified and prioritized. Through its Aviation Safety Program, NASA is developing technologies that will enable accurate, timely and intuitive information to be presented to pilots in flight for the detection and avoidance of atmospheric hazards. NASA has partnered with other government agencies, industry and academia to develop affordable and effective technologies for data-link cockpit weather information systems and to realize the goal of reducing weather-related accidents. As the first generation of viable data-link cockpit weather information systems is being fielded, NASA and its partners are continuing to develop system enhancements, operational guidelines and technologies for the next generation of these systems.

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## ADDITIONAL SOURCES

More information is available via the internet:

<http://awin.larc.nasa.gov/>  
<http://wincomm.grc.nasa.gov/>

## DEFINITIONS, ACRONYMS, ABBREVIATIONS

**ACARS:** Aircraft Communications Addressing and Reporting System  
**ADDS:** Aviation Digital Data Service  
**AGATE:** Advanced General Aviation Transport Experiments  
**AGL:** Above Ground Level  
**AOC:** Airline Operations Center

**AOPA:** Aircraft Owners and Pilots Association  
**ARINC:** Aeronautical Radio Incorporated  
**ASF:** Air Safety Foundation  
**ASIST:** Aviation Safety Investment Strategy Team  
**ASOS:** Automated Surface Observing System  
**ATC:** Air Traffic Control  
**ATN:** Aeronautical Telecommunication Network  
**AvSP:** Aviation Safety Program  
**AWIN:** Aviation Weather Information  
**EFB:** Electronic Flight Bag  
**EWxR:** Enhanced Weather Radar  
**FAA:** Federal Aviation Administration  
**FAR:** Federal Aviation Regulation  
**FBO:** Fixed Base Operator  
**FIS:** Flight Information Services  
**FIS-B:** Flight Information Services-Broadcast  
**FISDL:** Flight Information Service Data Link  
**FSS:** Flight Service Station  
**ft:** Feet  
**GA:** General Aviation  
**GAMA:** General Aviation Manufacturers Association  
**GIFTS:** Geosynchronous Imaging Fourier Transform Spectrometer  
**GMSK:** Gaussian Mean Shift Keying  
**GPS:** Global Positioning System  
**GTRI:** Georgia Tech Research Institute  
**ICAO:** International Civil Aviation Organization  
**IMC:** Instrument Meteorological Conditions  
**IP:** Internet Protocol  
**JSAT:** Joint Safety Analysis Team  
**JSIT:** Joint Safety Implementation Team  
**kHz:** Kilohertz  
**LEO:** Low Earth Orbit  
**MASPS:** Minimum Aviation System Performance Standards  
**MDCRS:** Meteorological Data Collection and Reporting System  
**MEO:** Medium Earth Orbit  
**METAR:** Aviation Routine Weather Report  
**MSL:** Mean Sea Level  
**NAS:** National Airspace System  
**NASA:** National Aeronautics and Space Administration  
**NCAR:** National Center for Atmospheric Research  
**NCWF:** National Convective Weather Forecast  
**NEXRAD:** Next Generation Weather Radar  
**NOAA:** National Oceanic and Atmospheric Administration  
**NWS:** National Weather Service  
**ODU:** Old Dominion University  
**RTCA:** Radio Technical Commission for Aeronautics  
**RTI:** Research Triangle Institute  
**SATCOM:** Satellite Communication  
**SIGMETS:** Significant Meteorological Observations  
**SITA:** Societe Internationale de Telecommunications Aeronautiques  
**TAMDAR:** Tropospheric Airborne Meteorological Data Reporting  
**UHF:** Ultra High Frequency  
**VFR:** Visual Flight Rules  
**VHF:** Very High Frequency  
**VMC:** Visual Meteorological Conditions

